SUBNANOSECOND LINEAR GaAs PHOTOCONDUCTIVE SWITCHING*

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Abstract

We are conducting research in photoconductive switching for the purpose of generating subnanosecond pulses in the 25 - 50 kV range. We are exploiting the very fast recombination rates of Gallium Arsenide (GaAs) to explore the potential of GaAs as a closing and opening switch when operating in the linear mode (the linear mode is defined such that one carrier pair is generated for each photon absorbed). The closing time of a linear GaAs switch is theoretically limited by the characteristics of the laser pulse used to activate the switch (the carrier generation time in GaAs is ~10^{-14} sec) while the opening time is theoretically limited by the recombination time of the carriers. The recombination time is several ns for commercially available semi-insulating GaAs. Doping or neutron irradiation can reduce the recombination time to less than 100 ps. We have observed switch closing times of less than 200 ps with a 100 ps duration laser pulse and opening times of less than 400 ps with neutron irradiated GaAs at fields of tens of kV/cm. The illumination source was a Nd:YAG laser operating at 1.06 µm.

Introduction

Photoconductive switching is an exciting switching technology that holds the promise of switching high voltages and high currents in very short times (<< 1 ns) [1]. Linear photoconductive switches have several advantages over conventional pulse power devices. Carriers are generated directly by the absorption of a photon in linear photoconductive devices. A laser is typically used as the illumination source to attain the high power densities necessary to generate copious carriers. Since the carriers are generated directly by photon absorption, the rise time of the device is determined directly by the rise time of the laser (carrier creation time ~10^{-14} sec) and there is no jitter associated with the switch. Laser control provides optical isolation of the trigger. Optical isolation allows convenient stacking of devices for series voltage holdoff. In addition, since there is no jitter, devices can conveniently be paralleled to increase current handling. Therefore, these devices can be easily scaled in voltage and current. Since very short pulse lasers are available today, rise times can approach picosecond time scales. Linear photoconductive switches are also one of the very few opening switches available at high voltages. All these characteristics (fast closing, no jitter, fast opening) combine to make photoconductive switches the only known candidate for direct microwave generation in the 500 MHz - 3 GHz region. This is one of three papers describing our work in photoconductive switching (see also "Avalanche Photoconductive Switching," M. D. Pocha et. al. and "Analysis of the Performance of Gallium Arsenide Photoavalanche Switches," W. T. White et. al.) Our work in linear photoconductive switching is concentrating on generating pulses and microwave waveforms in the 1 - 2 GHz region.

Theory of Operation

The phenomenon of photo-induced conductivity is quite simple in concept. In essence, a photon is incident on a material (semiconductor in this case) whose ionization energy is less than the energy of the photon. The photon is absorbed, releasing its energy to the semiconductor crystal structure, causing an electron-hole pair to be released into the conduction band (valence band for holes). The electron and hole are now free to participate in the conduction process. GaAs is a direct band-gap semiconductor with a band gap of 1.43 eV, which corresponds to a wavelength of about 860 nm. At wavelengths shorter than 860 nm, absorption will be very strong. This strong absorption leads to a very short absorption depth (several micrometers or several tens of micrometers). The very short absorption depths lead to narrow conduction channels at the surface of the crystal and very high current densities. If the crystal were perfect there would be no absorption at wavelengths longer than the wavelength corresponding to the band gap. In reality, the crystal is not perfect and there is absorption at wavelengths longer than the band gap wavelength at impurity sites and other crystal defect sites. This "extrinsic" absorption can be used to advantage to create larger conduction channels and a corresponding decrease in current density. Once the carriers are generated, the forces due to the field across the device accelerate the carriers toward the electrodes. Collisions with the crystal structure scatter the electrons and holes, limiting the velocity in the field direction. This scattering gives rise to the mobility. At high fields velocity saturation occurs limiting the concept of mobility concepts to low field. In general linear switches require fairly high laser intensities (several MW/cm^2) to switch successfully at high fields (and high voltages). After the laser light is removed from the switch, recombination removes the carriers from the conduction process. The recombination time of GaAs can be made as short as several picoseconds with the proper preparation, giving switch opening times of tens or hundreds of picoseconds. As the field is increased beyond a threshold value, the switch will only partially recover, leaving the device in a partially open state (the worst of all worlds from a power dissipation standpoint). This partially open state has been dubbed "lock on" by researchers at Sandia National Laboratory, Albuquerque [2] and will be used here also. The physics of this state is not well understood at this time but efforts are under way at LLNL to improve our understanding [3]. The practical implication of lock on is that the linear switch can be used as a fast closing and opening switch at low fields (below several tens of kV/cm, depending on device preparation) but becomes a very fast closing only switch at higher fields.

Experimental Setup

Our work is concentrating on linear and lock on operation at subnanosecond time scales. The material is GaAs or InP. The switches are tested in the transmission line test fixture shown schematically in Fig. 1 and photographically in Fig. 2. The line

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14. ABSTRACT
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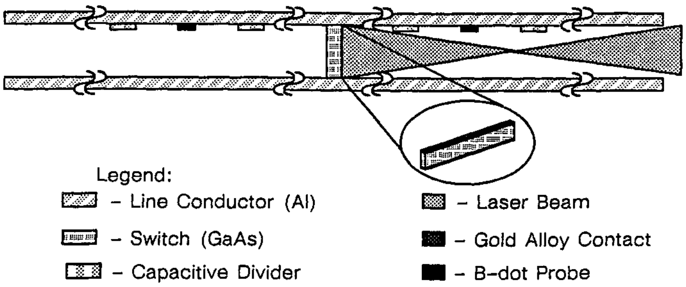


Figure 1. Block diagram of parallel plate transmission line test fixture.

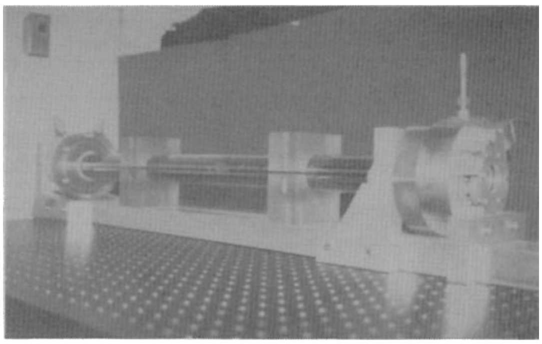


Figure 2. Photograph of parallel plate transmission line test fixture.

dimensions are 2 cm wide, 0.5 cm spacing (the field is approximately twice the voltage), and 1 m length, giving a characteristic impedance of 100 Ω and an electrical length of about 3 ns. Switch wafer dimensions are 1 x 5 x 20 mm with the laser illuminating the 5 x 20 mm face of the switch and the current flowing through 1 x 5 mm face. The field is across the 5 mm gap. It should be noted that the switch shorts the transmission line in the axial center and pulses are propagated in both directions from the switch, giving an effective switched impedance of 50 Ω. The switch is mounted in a demountable insert to allow for simple mounting in the line fixture and easy modification of the switch mounting. The entire transmission line fixture is enclosed in a pressure vessel with a 50 psig capability to facilitate pressurization with SF_6, air, or N_2 to enhance open state voltage hold off. The test fixture is pulse charged by a Blumlein producing a variable amplitude pulse with the shape shown in Fig. 3. A 100 - 200 Ω charge resistor is typically inserted in series with the line test fixture to limit late time currents. There are a total of six in situ fast pulse diagnostics in the test fixture. There are four capacitive dividers and two $\dot{B}$ probes with positions indicated in Fig. 1. These probes have bandwidths greater than 4 GHz. The in situ pulse diagnostics (capacitive dividers and $\dot{B}$ probes) were calibrated with a known pulse. The overall bandwidth of the diagnostic system is limited by the interconnecting cables to about 2 GHz. A Quantel YG501-30 laser is used to control the switch. This laser is a mode locked Nd:YAG having a pulse width (FWHM) of 100 ps and a maximum energy/pulse of 50 mJ. The laser is capable of operation at a repetition rate of up to 30 Hz. We do not use a homogenizer to ensure uniformity of illumination. We feared that the benefits of beam uniformity might be overshadowed by temporal degradation of the laser pulse by the homogenizer.

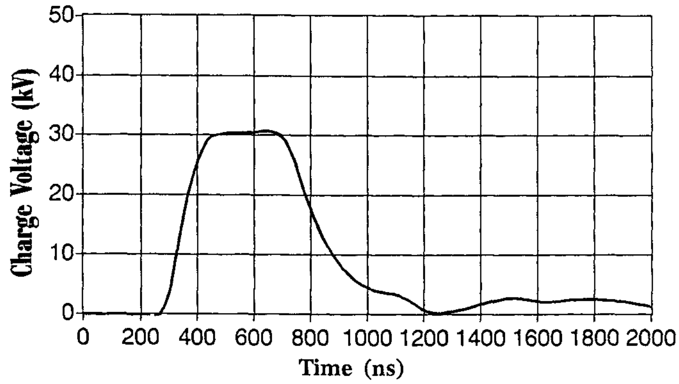


Figure 3. A representative charge pulse showing shape and duration.

Experimental Results

We are studying four main issues concerning linear photoconductive switching: open-state voltage holdoff, closing and opening switching speed, efficiency of laser control, and life time.

Open State Field

The theoretical bulk breakdown field for GaAs is 200 kV/cm. In realizable switch configurations, the attainable open-state field is limited by surface flashover of the GaAs. There are two ways to improve surface flashover: shape the field away from the surface or improve surface preparation. We are using both methods to improve the open-state field attainable with the switches. Our investigations have shown that, with no field shaping, the switch tends to flash over near the end in the high field region. To alleviate this problem, the switch holder shown in cross section in Fig. 4 was developed to shape the fields

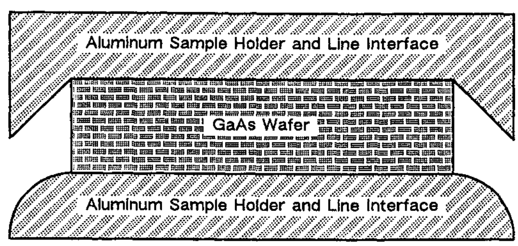


Figure 4. Cross sectional view of improved switch holder showing field shaping away from the non-illuminated surface of the switch.

away from the surfaces that were not illuminated by the laser. Since the triple junction (where the GaAs, aluminum, and insulating gas meet) is usually the point at which a flashover initiates, we are also attempting to embed the electrodes in the GaAs to relieve the fields at the triple junction along the illuminated face of the switch. Another area of research is surface coatings. Many insulating materials that can be used to coat the semiconductor have been shown to hold fields of > 200 kV/cm in SF_6. Coating with some of these materials improve the surface flashover properties of GaAs by varying amounts. Polyimide has shown the greatest improvement overall. Coated samples operate as reliably in atmospheric SF_6 as in pressurized SF_6 (this is not true of uncoated samples). As a result, the coatings also relax the requirement for a pressure vessel. Figure 5 shows graphically the maximum attainable

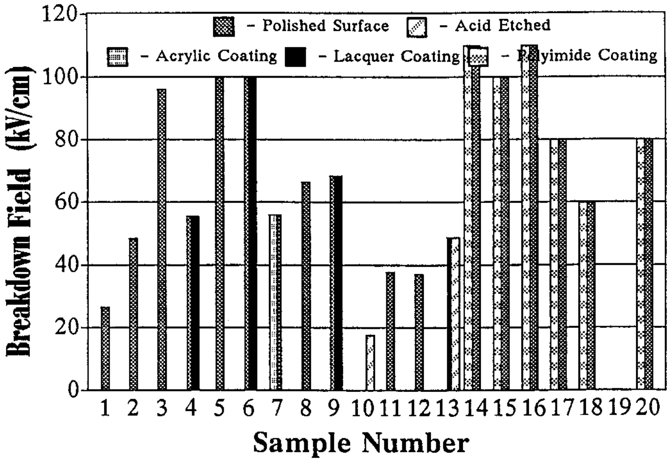


Figure 5. Plot of dark breakdown field for several samples.

field results to date. A severe problem with semiconductor materials in general and GaAs in particular is the variability of the semiconductor material. Several samples of GaAs prepared in exactly the same manner may have maximum attainable open state fields that differ by as much as an order of magnitude. We are studying uniformity of surface preparation to these variations among GaAs wafers.

Switching Studies

Three material types have been studied to date: semi-insulating LEC grown GaAs, Fe doped InP, and neutron irradiated LEC grown GaAs. While somewhat similar, each material behaves in a unique fashion. Figure 6 shows a representative pulse for the LEC

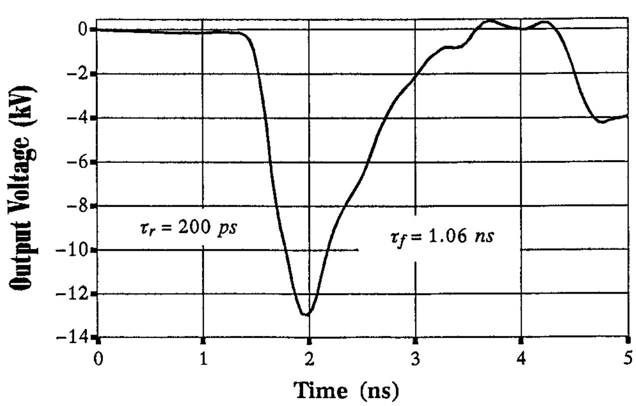
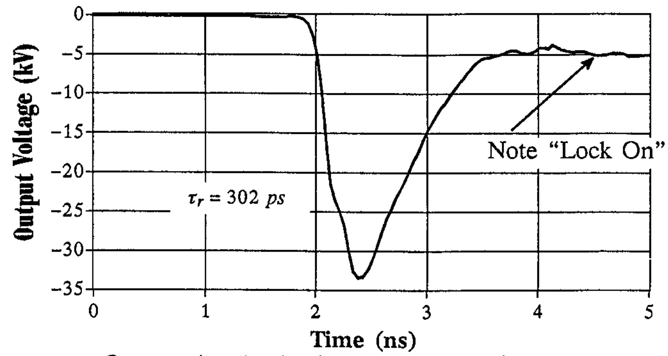
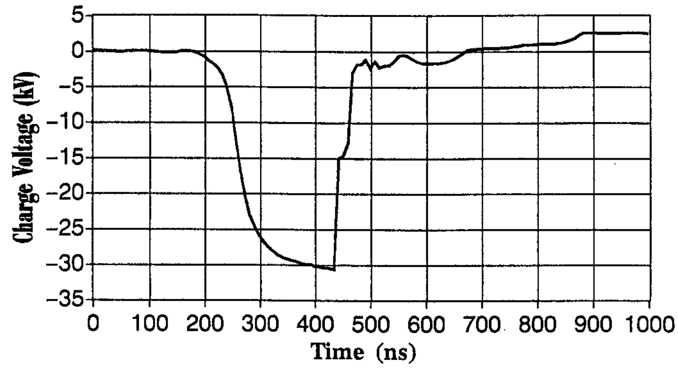


Figure 6. Typical LEC GaAs shot below lock on threshold. Charge voltage ~12 kV, Laser energy ~1.32 mJ.

grown GaAs switching experiments showing general pulse shape and typical time scales. The voltage for this shot was just below the threshold for lock on. Figure 7 shows a pulse and associated charge voltage for a charge well above the lock on threshold for LEC GaAs. It can be seen in Fig. 7a that the closing time



a. Output pulse showing fast rise and Lock On beginning



b. Charge voltage showing late time Lock On voltage

Figure 7. Plot of "lock on" semi-insulating GaAs switch behavior Laser energy ~ 2.1 mJ.

of the switch has not been significantly affected at higher field levels but that the switch no longer fully opens. Lock on seems to be related only to the field across the switch (we have also seen lock on in other geometries). Other researchers have also seen lock on[2] in direct band gap semiconductors. It has been theorized that lock on is related to Gunn domain formation[4]. We have found evidence that this theory may be valid[3] but results are not conclusive. The residual voltage left on the switch at long times (compare with the representative charge pulse in Fig. 3.) indicates high power dissipation in the switch. This high dissipation may reduce switch life and makes lock on operation much less attractive as a closing switch. Figure 8 is a plot of a representa-

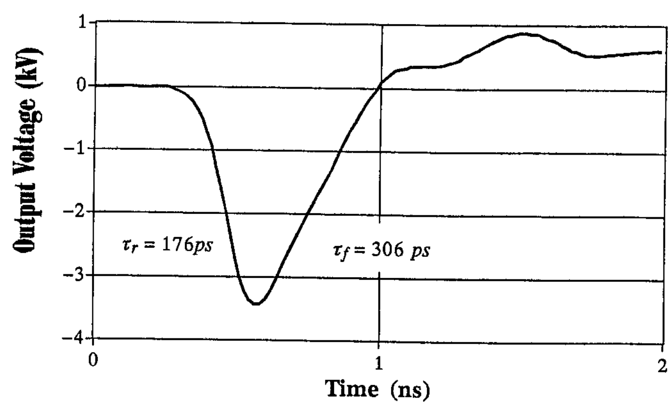


Figure 8. Representative neutron irradiated LEC GaAs pulse Charge voltage ~ 12.4 kV, laser energy ~ 227 μJ.

tive pulse with a neutron irradiated LEC GaAs device, while Fig. 9 shows a pulse from an InP:Fe switch. A comparison of Figs. 6, 7, 8, and 9 show that, while

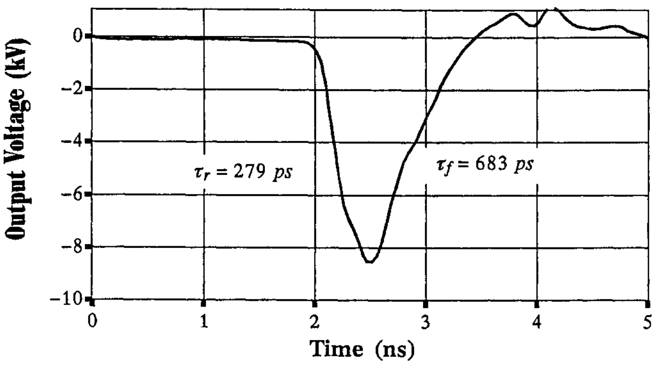
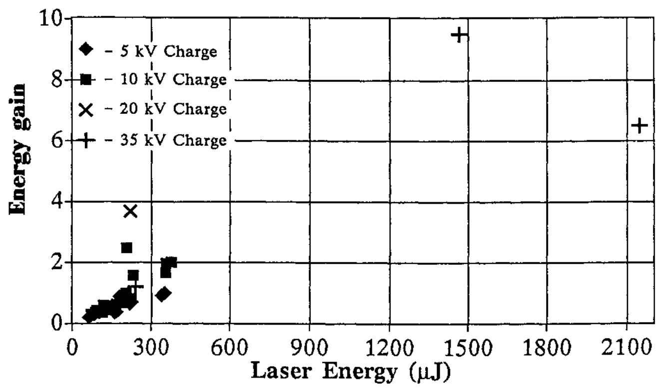
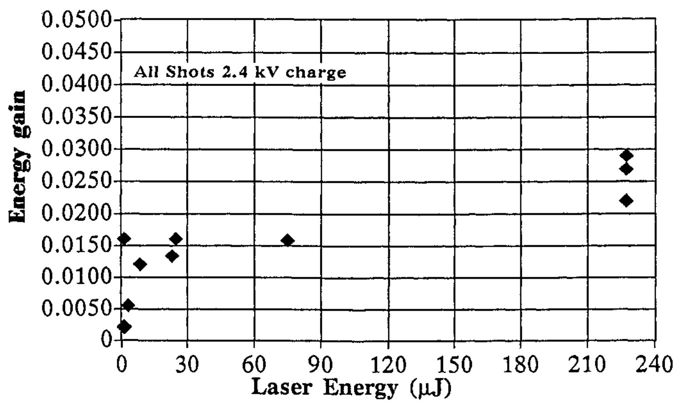


Figure 9. Typical pulse produced by InP:Fe switch Charge voltage ~8 kV, Laser energy ~540 μJ.

the shapes of the pulses are all similar, material properties do vary. LEC grown GaAs has the lowest lock on threshold of the materials investigated, followed by InP:Fe, and neutron irradiated GaAs (which may be as high as 60 kV/cm)[4]. LEC GaAs also has the highest gain (ratio of output electrical energy to laser energy), as seen in Fig. 10a, which is a plot of LEC GaAs gain, compared to Fig. 10b, which is a plot of neutron irradiated LEC GaAs gain. Figure 10 also



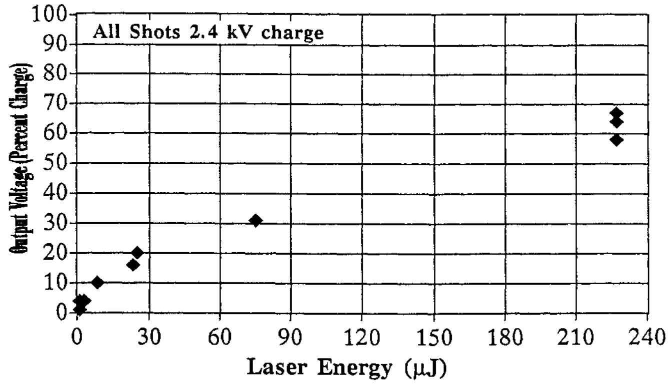
a. LEC GaAs, best gain observed to date



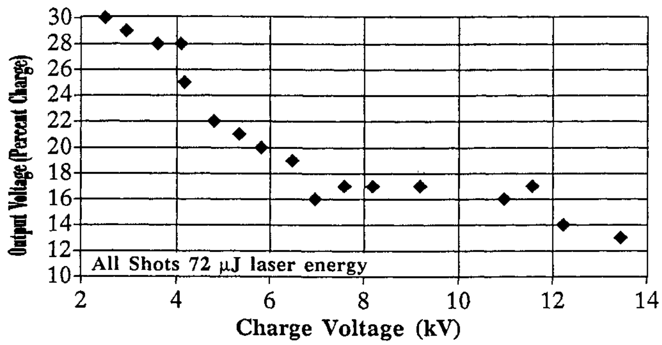
b. Neutron irradiated LEC GaAs

Figure 10. Plot of switch gain vs laser energy.

indicates that optimum gain increases with increasing field. Figure 11 shows plots of output voltage with variations in laser energy and charge voltage for neutron irradiated GaAs. It can be seen in Fig. 11



a. Plot of output voltage vs laser energy



b. Plot of output voltage vs charge voltage

Figure 11. Plot of output voltage vs laser energy and charge voltage.

that the output voltage is highly dependent on laser energy and much less so on charge voltage after velocity saturation has been reached. This dependence on laser energy indicates that there is a fairly narrow range of laser energy densities that are optimum for a given charge voltage. Comparing the data also indicates that the gain of the switch is related to the recombination time of the material. This result is not surprising since faster recombination will remove carriers from the conduction process faster. The mobility of the material may also be degraded by increased scattering from recombination centers.

Life Time

Switch life time is a definite issue for photoconductive switches used to switch high powers. The current densities in our devices have been < 5 kA/cm^2 in the majority of devices investigated in linear and lock on operation (with the laser penetrating entirely through the switch). Still, obvious surface damage has been observed after a few thousand shots at current densities of < 2 kA/cm^2 and repetition rates of ~ 1 Hz. In addition, the lock on field observed across the partially opened switch dissipates high power in the switch and limits long-pulse life time.

Conclusions

It is becoming clear that photoconductive switches have a potential place in general pulsed power switching and microwave generation in particular. Long pulses will be difficult to generate with the short recombination time direct band gap semiconductor switches, even in lock on mode. Photoconductive switches are ideal for the direct generation of microwave pulses and waveforms, particularly in large systems where many fast switches must be synchronized. Power densities approaching 30 MW/cm^2 have been observed. Efficiency of absorption and life time are still important issues barring the way to routine use of photoconductive switches in large systems.

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